INFRARED DETECTORS:
LOOKING BACK AND LOOKING AHEAD

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ABSTRACT

Over the past two decades, infrared detector technology has sparked a revolution in observational capability. This paper gives an overview of some of the major developments that have driven this revolution at far infrared and submillimeter wavelengths. We also discuss the activities of the Infrared, Submillimeter, and Millimeter Detector Working Group that is in the process of developing a roadmap for detector development.

INTRODUCTION

For a number of fundamental reasons, observations at infrared, submillimeter, and millimeter wavelengths are essential to the understanding of diverse astrophysical phenomena. These wavelengths are central to studies of cosmology and the evolution of galaxies because the expansion of the universe redshifts the bulk of the emission to long wavelengths. The bulk of the energy from objects as diverse as starburst galaxies, molecular clouds, and protostars is emitted in the infrared and submillimeter because of the influence of cosmic dust. Spectroscopy of many of the key cosmic constituents such as molecular hydrogen, neutral carbon, and water is best done in the infrared, submillimeter, and millimeter.

Advances in observations have usually been driven by the availability of suitable detectors. Because of the great scientific interest in these wavelengths, detector development in the infrared, submillimeter, and millimeter is very active. Especially at the long wavelengths, the support of NASA and other space agencies has been critical. Some of the most important technologies have come as the direct result of developments for specific space astronomy missions. This ***Workshop on Far-Infrared, Submillimeter, and Millimeter Detector Technology*** is a superb opportunity for the community of detector developers to exchange ideas and results. With the imminent launch of SIRTF, the commencement of operations for SOFIA in 2005, the launch of Herschel and Planck in 2007, and the anticipated development of even more powerful observatories such as the Single Aperture Far Infrared telescope (SAFIR), it is certainly timely to examine the status of long-wavelength detectors.

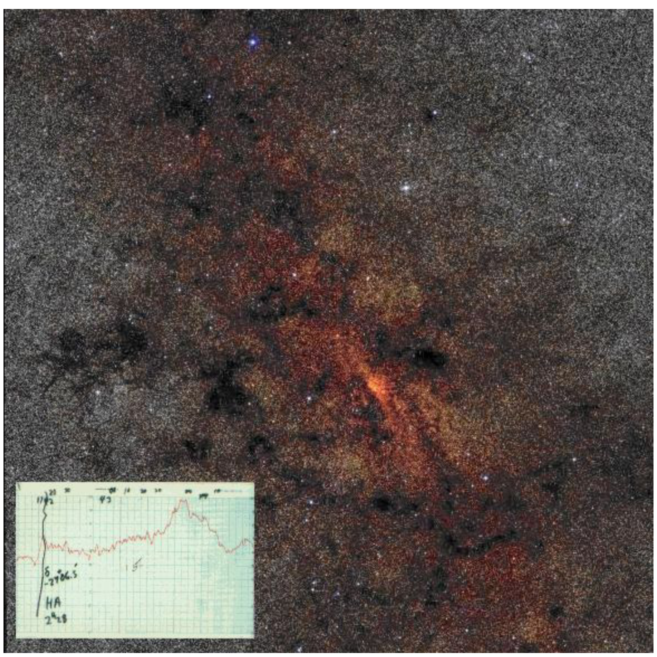

Figure 1. *Two Views of the Galactic Center: Single Element Detector (inset) [Becklin and Neugebauer] and 2MASS.*

THE ARRAY REVOLUTION

Astronomy has greatly benefited from the advances in semiconductor technology over the past few decades. The development of infrared arrays has yielded orders of magnitude increases in the observational capability. The advantages of large format arrays have been well documented, and they include greatly increased efficiency,

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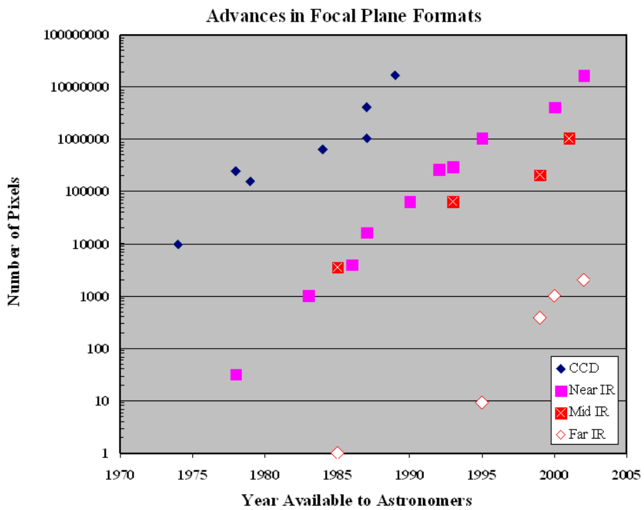

Figure 2. *The Advancement of Array Formats with Time.*

sensitivity, ability to accurately assess backgrounds, high precision photometry, and high precision positional information. ***Figure 1*** shows how far we have come in just a few decades. The inset shows an observation of the Galactic Center by Eric Becklin and Gerry Neugebauer done with a single element detector. The full picture is a view that was obtained with the 2MASS survey, taking advantage of 256x256 arrays originally developed for NICMOS on the Hubble Space Telescope.

Following the original observation by Moore[1] that the complexity of integrated circuits was doubling on roughly a yearly basis, the semi-conductor industry has maintained a phenomenal exponential rate of growth for close to 40 years. Similarly, the formats available to astronomy have shown the same kind of growth. ***Figure 2*** shows the dramatic increase in array sizes over the years for various kinds of astronomical sensors. The formats of near-infrared arrays, best exemplified by the 4096x4096 Next Generation Space Telescope (NGST) mosaic, are now rivaling the largest optical CCD's. At far-infrared wavelengths, the progress has been slower, where we have gone from the individually-wired pixels of the IRAS focal plane array (***Figure 3***) to the 32x32 array that will fly on SIRTF (***Figure 4***). Development work is underway to produce a 64x32 array for Herschel, scheduled to fly in 2007. Clearly, however, the longest wavelengths have yet to realize the full potential of increased array formats. One of the challenges in the next decade will be the construction of these very large far-infrared arrays.

NASA STRATEGIC PLANNING

NASA has a regular process for producing long-range plans that includes input from scientific community. Typically, strategic plans focus on the activities for the next 5-10 years, and they are updated every 3-year or so. Currently both the Astronomical Search for Origins (ASO) and Structure and Evolution of the Universe (SEU) themes are preparing new plans that will feed into the strategic plan for the Office of Space Science (OSS).

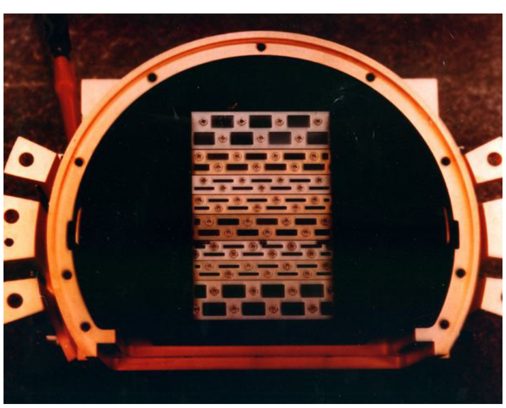

Figure 3. *IRAS Focal Plane*

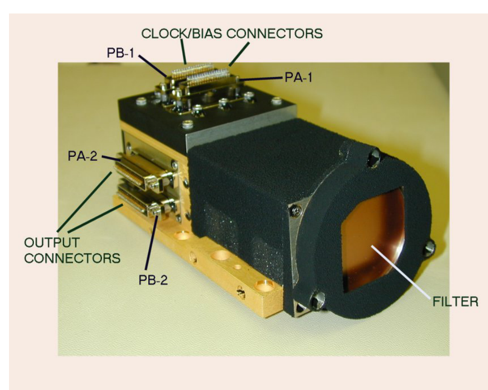

Figure 4. *SIRTF/MIPS 70 μm Array*

Because the Origins theme has a well-defined, funded program that extends through the next decade, it is anticipated that the new Origins strategic plan will be very similar to the 2000 version. The current plan includes HST, SIRTF, SIM, NGST, SOFIA, KEPLER, and TPF. In the longer term, the key mission concept that has been endorsed by the Decadal Survey is SAFIR. Unlike Origins, SEU does not have a similar funded list of missions. The expected focus of the SEU roadmapping activity will be the creation of a new initiative that includes the Laser Interferometer Space Antenna (LISA) and Constellation-X.

MISSION CONTEXT

A number of missions have been endorsed by either the Decadal Survey[2] or the Committee on Physics in the Universe[3]. Both studies have been conducted under auspices of the National Academy of Sciences. Two of the recommended missions will require significant advances in the state of the art in long wavelength detectors. They are the Single Aperture Far Infrared Telescope (SAFIR) (***Figure 5***) and a mission to study the polarization of the cosmic microwave background (CMBPOL). These mission concepts will require far-infrared arrays with 10^4 pixels, extended wavelength coverage, and in the case of SAFIR, pixel Noise Equivalent Powers as low as 10^{-21} $WHz^{-1/2}$. The potential reward for reaching these levels of performance will be an unprecedented advance in our knowledge of the inflationary Big Bang, the formation and evolution of galaxies, and the formation of stars and planetary systems.

Figure 5. *Concept for the Single Aperture Far-Infrared Telescope. [Ball Aerospace]*

Besides space missions, the sub-orbital program is an important element in the detector technology picture. With its decades-long lifetime coupled with the ability to quickly change instruments, SOFIA will play a critical role in future detector developments. At this workshop, SOFIA management endorsed the concept of devoting a portion of the future instrumentation resources to detector development. Such sustained support will be important to the health of the technology community.

Finally, in addition to enabling large missions, improved detector technology makes possible innovative smaller scale investigations. Recent examples of missions or potential missions that take advantage of opportunities created by detector technology include the Submillimeter Wave Astronomy Satellite (SWAS), the Next Generation Sky Survey (NGSS), and the AstroBiology Explorer (ABE).

IR SUB-MM, AND MM DETECTOR WORKING GROUP

The Infrared, Sub-millimeter, and Millimeter Detector Working Group (ISMDWG) was chartered by the Astronomy and Physics Division of NASA's Office of Space Science (OSS) to produce a roadmap of sensor developments needed to insure that the required infrared and sub-millimeter detectors are available and optimized to achieve the scientific goals of missions defined in the roadmaps for the ASO and SEU themes.

The charge of the ISMDWG includes:

1. An enumeration of the requirements for IR, Sub-mm, and millimeter wave detectors associated with the goals of the Theme roadmaps and the Decadal Survey.
2. An evaluation of the compatibility of existing detector technology with the foreseen missions.
3. An assessment of the current capabilities for design, fabrication, and testing of IR/Sub-mm detectors and associated readout technologies in the U.S. and abroad.
4. An assessment of the current state of IR/Sub-mm detector technology research and development.

The ISMDWG is chaired by Erick Young (University of Arizona). Because of the breath of technologies encompassed under the charter, the Working Group is organized into three subgroups:

1. 1 – 40 µm Detectors: Craig McCreight (Ames Research Center, Subgroup Chair), Terry Herter (Cornell), and Ian McLean (UCLA);
2. Long Wavelength Direct Detectors: Paul Richards (UC Berkeley, Subgroup Chair), Andrew Lange (Caltech), Harvey Moseley (Goddard Space Flight Center), and Erick Young (University of Arizona);
3. Coherent Detectors: Charles Lawrence (JPL, Subgroup Chair), John Carlstrom (Chicago), William Danchi (Goddard Space Flight Center), and Jonas Zmuidzinas (Caltech)

Additional members of the Working Group are Jay Frogel (NASA Headquarters), Eric Smith (NASA Headquarters), and Guy Stringfellow (University of Colorado).

To provide timely input into the OSS strategic planning process, the ISMDWG will produce a roadmap report by early June 2002. These findings will feed into the development of the strategic plan for the Astronomy and Physics Division.

ANTICIPATEED DEVELOPMENT CHALLENGES

1- 40 µm Detectors

In the 1 – 40 µm range, large format, hybrid detector arrays are available utilizing a number of detector materials including InSb, HgCdTe, and doped silicon. Generally, the technology involves a two-dimensional pixel array of photon detectors that is attached to a matching silicon readout integrated circuit. This hybrid technology is generally well advanced, and high performance detector arrays are available in formats as large as 2048 x 2048 pixels. The key challenges at these wavelengths will likely involve continuing the advancement of array formats, improving the wavelength coverage of available materials, and maintaining the manufacturing base for advance detectors.

Long Wavelength Direct Detectors

Beyond 40 µm, both photon and thermal detectors are used. Photon detectors directly convert incoming light into electronic carriers (or alternatively, "charge") which are then measured. The most prevalent long wavelength photon detectors use doped germanium in the photoconductive mode. These detectors have a long history in space astronomy beginning with IRAS and continuing to SIRTF. Germanium photoconductors have been used to produce the only kilo-pixel space qualified far infrared array. Despite their successes, bulk germanium photoconductors have significant limitations including restricted wavelength coverage, non-linear response, and sensitivity to ionizing radiation. These limitations have motivated work on other detector systems. Doped silicon impurity band conduction detectors are the devices of choice below 40 μm, and efforts to develop the far-infrared analogs are underway. Thermal detectors convert the photon energy into heat that raises the temperature of the sensing element, and some form of thermometer is then required to measure the temperature rise. Both semiconductor and a superconducting Transition Edge Sensors (TES) have been used to produce detectors of exquisite sensitivity. The primary development challenge for bolometer systems will be to address the systems issues associated with operating these arrays in space. For both long wavelength photon and thermal detectors, the construction of large arrays of detectors will be a major development thrust.

Coherent Detectors

Coherent detector systems amplify the incoming photon stream, preserving both phase and amplitude information. Consequently, coherent detectors are subject to a quantum mechanical limit to their sensitivity. This "quantum noise limit", expressed as a noise temperature, is given by $h\nu/k_B$, where h is Planck's constant, ν is the frequency, and k_B is Boltzmann's constant. Numerically, the quantum limit is 0.05ν K/GHz, or 50ν K/THz. In practice, the quantum limit is not important for ground-based or airborne telescopes, but is a serious issue for cold telescope in space, where direct detectors enjoy a large advantage. The signals in coherent systems are often downconverted in frequency prior to detection, and they have proven particularly useful in applications that require very high spectral resolution. Current performance of available coherent detectors is close to fundamental limits for frequencies below ~500 GHz, but far short at THz frequencies. The main technical challenges in coherent detectors are the need to extend good performance to the highest possible frequencies, the need for improved local oscillators, and the desire for large arrays of detectors.

GENERAL CONSIDERATIONS

The long wavelength detector community has proven its innovation and technical prowess through the development of very sophisticated systems. In many cases, the development of these systems has had very little commercial or military support, and NASA sponsorship has been one of the keys to advancement. Currently, the NASA grants program has been the principal source of funding for development of new detector concepts, while mission support has enabled the necessary detailed engineering to elevate mature sensors to the flight-ready status. As systems become more complicated, however, it may be necessary to create new modes of support to bridge the gap between developmental and mature systems.

The general issue of infrastructure maintenance is important for the long wavelength community. In many cases, there are only single sources for key technologies. Often these sources exist in university or national laboratories. In other cases, the key capabilities exist in industrial settings. Given the often long time scales for the development of mission concepts, mechanisms to maintain key capabilities will be needed to insure that the detectors will exist when the missions are ready.

REFERENCES

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2. Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board, National Research Council, 2001, ***Astronomy and Astrophysics in the New Millennium***, National Academy Press: Washington, DC. [Decadal Survey].

3. Committee on the Physics of the Universe, M. Turner, Chair, 2002, ***Connecting Quarks with the Cosmos: Eleven Science Questions for the New Centur***y, National Academy Press: Washington, DC.